The Extreme Ultraviolet Airglow of N_2 Atmospheres

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Extreme ultraviolet (EUV) airglow observations at Titan, Triton and Earth provide a rigorous test for models of N_2 atmospheres. This is primarily because the emissions are produced in dramatically different environments. EUV spectra obtained by the Voyager Ultraviolet Spectrometer (UVS) at Titan and Triton are dominated by emission arising from electron impact on N_2 and by photodissociative ionization of N_2. Spectral analyses of the UVS data originally showed that the N_2 Carroll-Yoshino (CY) (0,0) band near 95.86 nm, the (0,1) band near 98.05 nm and the NII 108.5 nm multiplet are the brightest EUV airglow features. But the detailed processes leading to their intensity distribution are only now becoming clear. Model results have shown that the (0,0) band is optically thick and that photoelectron excitation followed by multiple scattering redistributes nearly all (0,0) band emission to the (0,1) band. Summing all emissions from other N_2 bands and NI multiplets near the (0,0) band excited by the solar EUV and X-ray irradiance indicated that the (0,0) band was misidentified. Many of these other emissions are now identified in new high-resolution terrestrial airglow spectra. The distribution of EUV airglow intensity at Triton is different than at Titan and new results are presented here from the same multiple scattering model adapted to Triton. It is found that the ratio of the (0,1) band to the blended emission near the (0,0) band is higher at Triton than at Titan and that the integrated intensity between 94.2-99.6 nm is 2.6 R at Triton, all consistent with UVS observations.

1. INTRODUCTION

Ever since Voyager 1 observations confirmed that Titan's atmosphere was almost entirely N_2, EUV airglow data obtained there by the UVS have received much scrutiny. Although the spectra appeared similar to electron impact emission spectra of N_2 obtained in the laboratory [*Broadfoot et al.*, 1981], the distribution of intensity reported among the various features was inconsistent with both laboratory observations and observations of the Earth's airglow [*Hunten et al.*, 1984].

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Since it was clear early on that photoelectrons alone could not explain the UVS observations, some studies invoked photodissociative ionization of N_2 and others included a magnetospheric source of energetic particles to model the data. However, models could not reproduce either the absolute or the relative intensities of the brightest EUV features reported in the data [*Strobel and Shemansky*, 1982; *Hunten et al.*, 1984; *Strobel et al.*, 1991; *Strobel et al.*, 1992; *Gan et al.*, 1992; *Galand et al.*, 1999].

Interest in the problem was revived following the Voyager 2 encounter of Triton's N_2 atmosphere in 1989. Although emissions arising from electron impact on N_2 were also evident in the Triton EUV airglow spectrum, the distribution of emission was different than that of Titan [*Broadfoot et al.*, 1989; *Strobel et al.*, 1991]. This added still another piece to an already complex and unresolved puzzle.

It has been over 20 years since the Voyager 1 Titan encounter and a wealth of new results have now put the UVS observations of Titan and Triton into a clearer context than before. These include spectroscopic details of the N_2 molecule from the laboratory, results from radiative transfer models and new observations of the Earth's airglow. Together, they suggest that the distribution of EUV emission observed by the Voyager 1 UVS at Titan can be explained by solar forcing alone and that one of the brightest features had been misidentified in spectral analyses [*Stevens*, 2001]. Aeronomers now await new higher resolution Titan airglow data from the Ultraviolet Imaging Spectrograph (UVIS) on the Cassini spacecraft.

This chapter summarizes the most important new advances that contribute to this revised view of Titan's EUV airglow and their impact on models of Triton's airglow. For simplicity, this work focuses only on UVS disk observations and only on the brightest features reported in the EUV spectra heretofore. These emissions are modeled using photoelectron impact on N_2 and photodissociative ionization of N_2 exclusively. Comparisons are made with recent observations of Earth's EUV airglow at high spectral resolution where identification of spectral features in the lower resolution UVS data is ambiguous.

2. THE EUV OBSERVATIONS

The EUV is defined herein to include wavelengths between 52-110 nm where the lower bound is the limit of the UVS observations and the upper bound is set to include the relatively bright NII 108.5 nm multiplet. The UVS data from Voyagers 1 and 2 have provided the only EUV airglow data from Titan and Triton to date. But the UVS spectral resolution is ~3.3 nm so that many emissions in this complex wavelength region are blended together. Figure 1 shows a comparison of disk-averaged UVS spectra from the sunlit sides of Titan and Triton. The brightest portion of their EUV airglow is the focus of this chapter.

The UVS airglow data from Titan are brighter and of higher quality than from Triton. The three brightest EUV features at Titan are listed in Table 1 and were originally reported to be the N_2 Carroll-Yoshino (CY) $c_4'^1\Sigma_u^+ - X^1\Sigma_g^+(0,0)$ band near 95.86 nm, the CY(0,1) band near 98.05 nm, and NII 108.5 nm [*Broadfoot et al.*, 1981; *Strobel and Shemansky*, 1982; *Hall et al.*, 1992]. The CY(0,v'') bands (also called the c_4' bands or simply the c' bands) are strongly excited by photoelectron impact [*Ajello et al.*, 1989] and their identification at Titan and Triton was primarily based on the similarity of the airglow spectra to electron impact emission spectra observed in the laboratory. NII 108.5 nm is only weakly excited by photoelectron impact but strongly excited by photodissociative ionization of N_2 [*Strobel et al.*, 1991]. UVS EUV airglow uncertainties at Titan were estimated by *Strobel et al.* [1992] and are included in Table 1. Note that a wavelength range is provided in the first column, which spans the UVS spectral resolution around each feature.

This study adopts the Voyagers 1 and 2 UVS calibration revision suggested by *Holberg et al.* [1982; 1991], which is a factor of 1.6 downward for the wavelengths 91.2-105.0 nm. This UVS calibration has yielded good agreement with stellar spectra observed by the Hopkins Ultraviolet Telescope [HUT; *Kruk et al.*, 1997]. The downward revision suggested by *Holberg et al.* is extended here to include the NII 108.5 nm multiplet [*Strobel et al.*, 1991; *Strobel et al.*, 1992].

For comparison, the most relevant EUV Earth airglow data were recently obtained by the Far Ultraviolet Spectrometer Experiment (FUSE). The FUSE data have a spectral resolution that is ~0.0075 nm [*Feldman et al.*, 2001] and the nadir-viewing observations are used here to confirm proposed emission features in the UVS spectra from Titan and Triton near the CY(0,0) band.

3. MODELING APPROACH

Until recently, models of Titan's EUV airglow used the relatively large laboratory measured electron impact emission cross-section for CY(0,0) [*Ajello et al.*, 1989] which yielded CY(0,0) intensities six times brighter than CY(0,1). But perhaps the greatest challenge at Titan is that the optical depth of CY(0,0) rotational lines near peak photoelectron production is extremely high ($>10^4$). If photoelectrons excite the (0,0) band at Titan, that emission should be multiply scattered and redistributed to the more optically thin (0,1) band [*Conway*, 1983; *Ajello et al.*, 1989; *Strobel et al.*, 1991]. If CY(0,0)/CY(0,1) is near unity as reported from spectral analyses of UVS data, this photon redistribution requires another source to explain the CY(0,0) brightness. This source, moreover, would have to produce (0,0) band emission above Titan's exobase [*Shemansky et al.*, 1995].

In light of the fact that the (0,0) band is weak or absent in higher resolution airglow data from the Earth and that the spectrum is complex near 95.86 nm [*Gentieu et al.*, 1981; *Morrison et al.*, 1990; *Feldman et al.*, 2001], it seems possible that the CY(0,0) identification was not correct. A quantitative study of all known emission features in the Titan EUV airglow arising from known solar-driven processes now suggests that this is the case. The most important factors leading to this conclusion are summarized below.

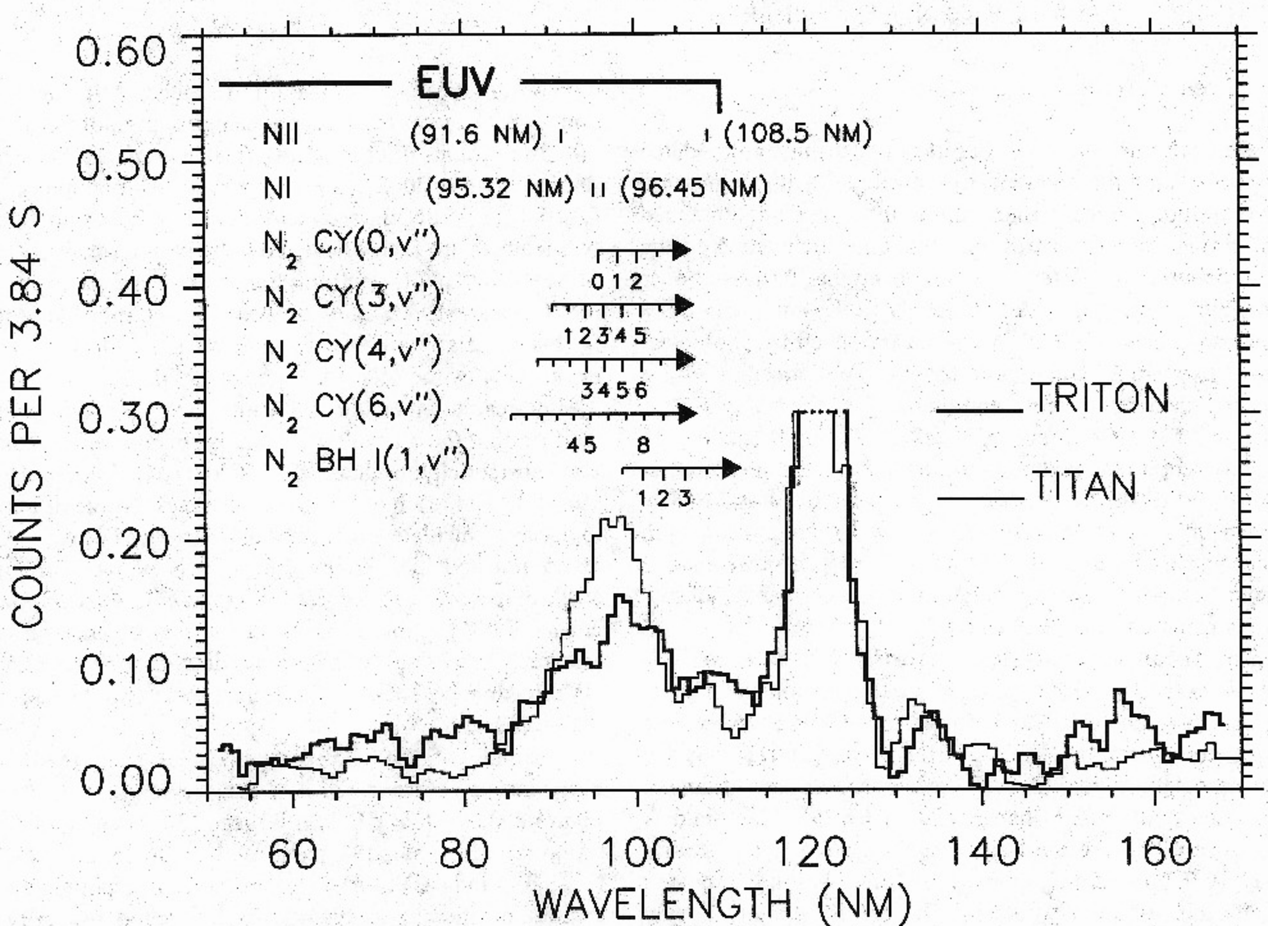


Figure 1. A comparison of uncalibrated disk-averaged UVS spectra where the Titan airglow spectrum is normalized to the Triton spectrum in the 108.5 nm region [reproduced with permission from *Broadfoot et al.*, 1989]. Note that the Lyman-α region near 121.6 nm is removed. Important NI multiplets, NII multiplets and N_2 bands between 91-110 nm that have been identified in FUSE terrestrial airglow spectra are labeled with a wavelength or numbered. Shorter N_2 band tick marks indicate emissions that are uncertain or severely blended in the FUSE data.

TABLE 1

VOYAGER UVS AIRGLOW OBSERVATIONS AND MODEL RESULTS

Wavelength (nm)	REPORTED IDENTIFICATION[a,b]	PROPOSED IDENTIFICATION[c]	TITAN		TRITON	
			Data (R)[d]	Model (R)[c]	Data (R)[e]	Model (R)[f]
95.86 ± 1.6	N_2 CY(0,0)	NI (96.45, 95.32 nm) + Others	8 ± 50%	6.7 (1.4, 1.3)	~0	0.8
98.05 ± 1.6	N_2 CY(0,1)	N_2 CY(0,1) + Others	6 ± 50%	9.4	2-3	1.8
108.5 ± 1.6	NII	NII	8 ± 50%	9.7 (7.9)	1.2-5	1.0

[a] *Broadfoot et al.* [1981]; *Strobel and Shemansky* [1982]
[b] *Broadfoot et al.* [1989]
[c] Photodissociative ionization in parentheses. Yields revised from *Stevens* [2001] (see text): $\varphi_{96.4}$=0.021, $\varphi_{95.3}$=0.019, $\varphi_{108.5}$=0.110
[d] *Strobel et al.* [1992]
[e] *Strobel et al.* [1991]
[f] This work (0% CH_4, $\tau_{CY(0,1)}$«1, 8% $c_4'(0)$ predissociation)

3.1 Titan: Progress Since Voyager 1

Recently the Titan EUV airglow spectrum was modeled by calculating the photoelectron excited CY(0,v'') emission in extremely optically thick conditions. The model included all known loss processes and explicitly included both the redistribution and loss of photons from the (0,0) band over multiple scatterings. All other N_2, NI and NII EUV emissions between 92.0-101.5 nm produced by photoelectron excitation and photodissociative ionization were treated separately for conditions of the Voyager 1 encounter at Titan [*Stevens*, 2001].

Two important inputs to the model are the predissociation yield of the $c_4'(0)$ state and the solar EUV and X-Ray irradiance. The solar irradiance below 45 nm controls both photoelectron production of $c_4'(0)$ and photodissociative ionization of N_2. Predissociation and the solar irradiance are considered separately below.

The predissociation yield of $c_4'(0)$ was measured by *Shemansky et al.* [1995] and for the temperatures in Titan's upper atmosphere it was reported to be 0.125. (Note that typesetting error in Table 2 of *Stevens* [2001] shows a predissociation yield of 0.120, which should be exchanged with the quoted (0,1) band yield of 0.125). This yield is significant because the large branching ratio to the ground state (0.73) radiatively traps (0,0) band photons. Repeated scatterings effectively increase the predissociation loss by about a factor of three above the optically thin value [*Stevens et al.*, 1994]. Photons are simultaneously redistributed to the (0,1) band where extinction by CH_4 and N_2 itself contribute to loss from the CY(0,v'') system. As a result, less than 25% of $c_4'(0)$ production appears in the (0,v'') progression and almost all of this is in the (0,1) band.

Previous EUV airglow models of Titan and Triton [*Strobel et al.*, 1991; *Strobel et al.*, 1992; *Gan et al.*, 1992] used the solar EUV and X-Ray irradiance of *Hinteregger et al.* [1981], SC21REFW. However, there is now considerable evidence that the EUV and X-Ray irradiance at these wavelengths is larger than in SC21REFW [*Richards et al.*, 1994; *Warren et al.*, 1998; *Bailey et al.*, 2000; *Bishop and Feldman*, 2002]. The quiet sun irradiance used in the airglow models presented here is from *Woods et al.* [1998] and is about a factor of two greater than SC21REFW for wavelengths below 45 nm. Scaling to active sun conditions of the Voyager 1 Titan encounter increases CY(0,1) and NII 108.5 nm nadir viewing intensities for these two features which are now consistent with reported observations. Table 1 shows model-data comparisons for CY(0,1) and the 108.5 nm multiplet where the modeled NII 108.5 intensity employs the yield of 0.11 recently inferred from data obtained by HUT [*Bishop and Feldman*, 2002]. CY(0,1) was calculated to be 81% of the 98.05 nm UVS feature at Titan.

Photodissociative ionization produces NI and NII emission at many discrete wavelengths in addition to NII 108.5 nm [*Samson et al.*, 1991; *Meier et al.*, 1991; *Bishop and Feldman*, 2002]. Two important NI multiplets near CY(0,0) at 95.86 nm are near 95.32 and 96.45 nm. These two features are each calculated to be brighter than CY(0,0) or any other photoelectron excited N_2 band at 95.86±1.6 nm. Calculated intensities of these NI multiplets and other N_2 bands nearby allowed for a Titan EUV airglow driven exclusively by the solar EUV and X-ray flux.

High-resolution nadir viewing Earth airglow spectra confirm that the NI multiplets and N_2 bands near 95.86 nm are substantially brighter than CY(0,0) [*Gentieu et al.*, 1981]. In fact, each of the eleven brightest N_2 bands and NI multiplets calculated for the Titan airglow between 92.0-101.5 nm and blended by the UVS is now identified in airglow spectra from the Earth [*cf. Stevens*, 2001; *Feldman et al.*, 2001]. Note that where there is ambiguity in assigning individual N_2 band emissions to the two blended UVS features in Table 1, the nearest feature to the emission is chosen.

A sample of the new data available from the FUSE instrument is shown in Figure 2 for a region near 95.86 nm. Figure 2 shows that CY(0,0) is weak (30 R) compared to a group of three blended features near 96.45 nm (85 R). CY(3,3) and CY(4,4) are excited by photoelectron excitation whereas NI 96.45 nm is excited primarily by photodissociative ionization.

One difficulty in establishing yields from NI and NII multiplets from the laboratory is that a synchotron continuum, from which yields are inferred, is significantly different than the solar EUV irradiance [*Meier et al.*, 1991]. Yields inferred from airglow data can therefore be more reliable. The reported FUSE NII 108.5 nm intensity of 400 R is scaled downward by 23% for the photodissociative ionization contribution to this feature [*Bishop and Feldman*, 2002]. A NI 96.45 yield is then inferred by assuming that the NI 96.45/NII 108.5 ratio inferred by *Meier et al.* [1991] is maintained. This lower yield of 0.021 is used in the results shown in Table 1 and produces 59 R in the terrestrial 96.45 feature or 69% of the blend in Figure 2. The new NI 95.32 nm yield similarly preserves the relative brightnesses of the multiplets and is not inconsistent with the FUSE data, although NI 95.32 nm not shown in Figure 2 is blended with OI emission.

3.2 Modeling CY(0,v'') on Triton

The solar driven EUV airglow is much weaker on Triton due to both its greater heliocentric distance and to the lower solar activity during the observations [*Broadfoot et al.*, 1989]. Following the procedure of *Stevens* [2001], the quiet sun spectrum [*Woods et al.*, 1998] was scaled to the conditions of the Voyager 2 encounter on August 25, 1979 ($F_{10.7} \sim 180$). A comparison of the solar EUV and X-Ray fluxes at 1 A.U. during the Titan and Triton UVS observations is shown in Figure 3. The photon flux integrated over the wavelengths shown is 79% of that for Titan. By also considering the greater heliocentric distance, the intensities of all calculated emission features are uniformly less by a factor of 12.6 compared to Titan.

The CH_4 mixing ratio on Triton is orders of magnitude smaller than on Titan [*Smith et al.*, 1982; *Broadfoot et al.*, 1989] so that CH_4 extinction is negligible. The extremely cold temperature (~80 K) near peak production on Triton [*Broadfoot et al.*, 1989], limits the population of the N_2 ground states to the lowest rotational levels. Therefore absorption of CY(0,1) by the accidentally resonant and predissociated N_2 Birge-Hopfield BH I $b^1\Sigma_u - X^1\Sigma_g^+(2,0)$ band [*Stevens et al.*, 1994] is also negligible. The cold temperatures at Triton also have the effect of reducing the predissociation yield from 0.125 on Titan to 0.08 [*Shemansky et al.*, 1995].

Using the Titan $c_4'(0)$ photoelectron excitation rates of *Stevens* [2001], the multiple scattering model was run for an N_2 atmosphere without CH_4, without BH I(2,0) absorption and with an optically thin predissociation yield of 0.08. CY(0,1) photons that reach the lower boundary of the model under these conditions are assumed to be lost. The resultant nadir viewing $(0,v'')$ band intensities were scaled down to reflect the different solar forcing at Triton discussed above. All other NI and CY($v'\neq0$) emission features were calculated assuming optically thin conditions and similarly scaled to solar conditions at Triton during the Voyager 2 encounter.

4. RESULTS

4.1 Triton

The loss of $c_4'(0)$ photons at Triton is roughly divided between CY(0,1) escape from the atmosphere, predissociation and CY(0,1) loss at the surface. The CY(0,1) nadir viewing intensity is calculated to be 1.6 R (1.8 R for the feature) and the 95.86 nm blend is 0.8 R as shown in Table 1. Given the uncertainties in the UVS EUV airglow data at Titan and the low signal at Triton, the agreement in Table 1 is acceptable and far better than obtained using the optically thin (0,0) to (0,1) band electron impact emission cross sections of 6 to 1. Since the calculated 98.05 nm/95.86 nm ratio for Triton is substantially larger than for Titan and the integrated 94.2-99.6 nm intensity is also consistent with observations, the evidence mounts for the misidentification of the 95.86 nm UVS feature at Titan.

4.2 CY(0,v'') Photon Redistribution

Aside from absolute brightness, the primary difference between the Titan and Triton EUV airglow is the brightness of CY(0,1) relative to the 95.86 nm blend. The primary causes are colder temperatures and less CH_4 at Triton. The colder temperatures reduce predissociation and produce an environment where CY(0,1) is more optically thin to N_2 BH I(2,0), leading to more (0,1) band emission observed. Less CH_4 at Triton also allows preferentially more CY(0,1) to escape since the 95.86 nm blend has a significant contribution from photodissociative ionization, which is excited much higher in the atmosphere [*Strobel et al.*, 1991].

Feldman et al. [2001] reported a CY(0,1)/CY(0,0) ratio of 2.3 for the Earth's airglow using FUSE observations, much lower than the Titan and Triton model results (>30). CY($0,v''$) rotational lines are Doppler broadened, so the warmer temperatures on Earth near peak photoelectron production not only populate more rotational levels but also increase the rotational line widths. For a given production rate, this reduces the amount of CY(0,0) self-absorption and the CY(0,1)/CY(0,0) ratio, consistent with observations. Warmer temperatures also enhance BH I(2,0) extinction of CY(0,1), further reducing the ratio.

Results from a multiple scattering model of the Earth's airglow by *Stevens et al.* [1994] show that for a nadir viewing geometry and an optically thin predissociation yield of 16.5%, the calculated CY(0,1)/CY(0,0) ratio is ~3. Although this ratio is in reasonable agreement with FUSE observations the CY(0,0)+CY(0,1) intensities are only 9-46 R depending on solar activity, more than a factor of two less than the 98 R reported. However, since the earlier *Stevens et al.* analysis used SC21REFW and given that recent work suggests a larger solar EUV flux than this, more detailed analysis of the FUSE data for the moderate solar activity is required and is underway.

5. SUMMARY AND FUTURE WORK

A revised view of the EUV airglow on Titan and Triton is presented that is a consequence of an elaborate multiple scattering model for calculating the redistribution of photons from the optically thick CY(0,0) band. A survey of all known features excited by the sun in this complex region of emission shows that a blend of N_2 bands and NI multiplets near 95.86 nm together constitute the UVS feature originally reported as CY(0,0). Good agreement is found with UVS data at Titan to within experimental uncertainties and new high resolution observations from Earth's airglow confirm that CY(0,0) is weak compared to neighboring emission features. New model results for

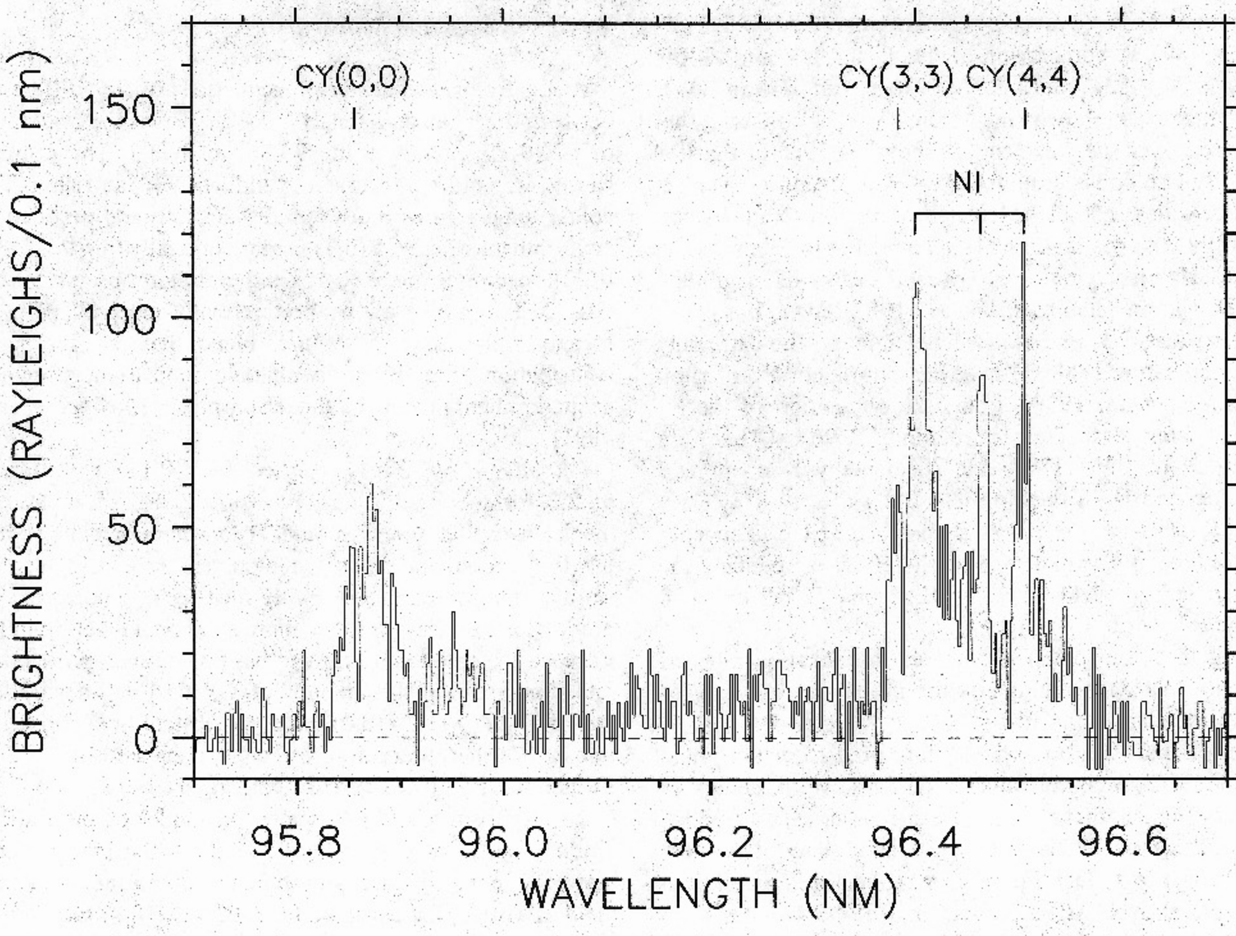
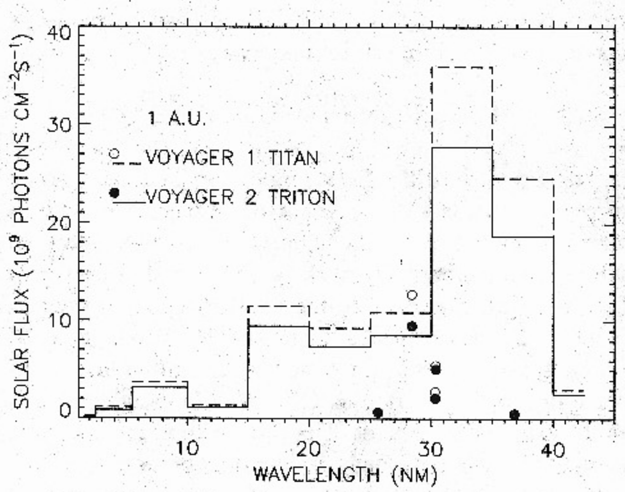


Figure 2. High-resolution terrestrial EUV airglow data of FUSE [from Figure 2 of *Feldman et al.,* 2001]. The data were taken on September 24-25, 1999 at a time of moderate solar activity ($F_{10.7} \approx 130$). Spectral analyses of the UVS airglow data at Titan and Triton argued that CY(0,0) dominates in this region. The UVS spectral resolution is over three times the wavelength region shown in this figure, so that these emissions and others were severely blended at Titan and Triton producing one feature near 95.86 nm.



Triton's EUV airglow presented here are also in agreement with UVS data and substantiate this result.

Several advances since the Voyager encounters of Titan and Triton have contributed to this new picture. These include new evidence for a larger EUV and X-Ray solar irradiance, a quantitative determination of the $c_4'(0)$ predissociation yield, neighboring NI emissions found to be produced by photodissociative ionization, and a downward revision to the UVS EUV calibration.

Figure 3. The solar irradiances used in the calculation of the EUV airglow at Titan and Triton. Symbols indicate irradiances of discrete lines and are not included in the flux for the wavelength bins.

If a solar EUV and X-Ray irradiance is used that is about a factor of two larger than SC21REFW and the downward revision of the UVS EUV calibration is adopted, the EUV airglow intensities at Titan and Triton are much better understood. The most pressing need in this area is to isolate and identify the emissions near 95.86 nm in Titan's airglow. The UVIS on the Cassini spacecraft can help with a projected spectral resolution of better than 0.5 nm [*McClintock et al.*, 1993]. If the 95.86 nm UVS feature is primarily a blend of neighboring NI multiplets and CY N_2 bands, then the EUV airglow observed by the UVS at Titan and Triton can be placed far more clearly in the context of Earth's airglow.

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